PROBABILITY DISTRIBUTIONS OF HIGH-ENERGY SOLAR-HEAVY-ION FLUXES FROM IMP-8: 1973-1996

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Abstract

We present probability distributions for the fluxes and event-integrated fluences of solar He, CNO, and Fe ions at high energies relevant to space-system design, based on observations from the University of Chicago's Cosmic Ray Telescope on IMP-8 in 1973-96. We compare the observed distributions to CREME96, whose new solar models are shown to produce realistic, extreme-worst-case ($\sim 99^{+}\%$ confidence level) environments. The probability distributions show that a modest reduction in the reliability requirement (from ~99% to ~90-95% confidence level, for example) can significantly reduce the severity of the heavy-ion hazard. This reduction factor is larger for solar heavy ions than for solar protons, and the exact amount of the reduction will depend critically upon other factors, such as device sensitivity, shielding, and orbit. We also show predictions of mission-accumulated solar-heavy-ion fluences as functions of confidence level and mission duration.

I. Introduction

Spacecraft designers are often required to assess system performance in "worst case" ionizing-radiation environments (as specified at a given confidence level) or to quote an upper bound on the total dose, displacement damage, or number of single-event effects in a mission of specified duration (again, at a given confidence level). To make such probabilistic assessments requires an extensive experimental database on the variability of the relevant particle fluxes in space. Feynman *et al.* [1] have previously developed such a database and assessment tool for solar protons (hereafter referred to as JPL91).

At present no comparable tool exists for heavy ions (with atomic number $Z \geq 2$), which are also accelerated to high energies in large solar particle events (SPEs). Moreover, in many applications these solar heavy-ions can be just as or even more important than protons. For example, although the average alpha-to-proton ratio in solar particle events is only 3.6% [2], alpha particles can cause much more displacement damage (by as much as a factor of ~40 [3]) than protons of the same energy. Assessing degradation due to displacement damage in an extended mission therefore requires estimates of the accumulated fluences of both protons and alphas. Solar heavy ions can also be a significant source of single event upsets (SEUs) [4], [5]. In some cases, system designers must guarantee an upper limit on the total number of satellite outages (for example, due to single-event latch-up) or hard failures (due to single-event burnouts) during a mission. Depending upon device characteristics, shielding, time in the solar cycle, and mission duration, the accumulated fluence of solar heavy ions can also be a major contributor to these effects.

Previous efforts at modeling solar heavy ions have had several shortcomings. The solar proton flux generally provides only a poor indicator of the concomitant heavy ion flux [6]. This fact presumably reflects the complexity of the acceleration process, the different charge to mass ratios of these ions [7],[8], and perhaps variability in the source plasma from which the high-energy ions are accelerated [9], none of which is fully understood. Thus, models which estimate heavy ion fluxes by using low-energy abundance ratios to scale from protons are generally unreliable, especially at the high energies relevant for space system design. Semi-empirical formulations [5], [10], which use theoretical models to extrapolate from lower-energy heavy-ion measurements, have shown similar problems [4], [11].

The new results presented here use direct measurements of solar heavy ions at energies sufficiently high to penetrate at least ~100 mils of aluminum, the typical minimum satellite shielding. The University of Chicago's Cosmic Ray Telescope (CRT) [12] aboard the IMP-8 spacecraft, which is presently a unique source of such data, has provided nearly continuous monitoring of the near-Earth interplanetary particle environment since its launch in October 1973. The IMP-8/CRT solar heavy-ion data have previously been used in a detailed analysis of SEU rates aboard TDRS-1 and LEASATs in the major solar particle events of 1989-92 [4]. The IMP-8/CRT heavy-ion measurements for the October 1989 solar particle episode, along with GOES proton data [13], are the basis of the "99%-confidence-level worst case" event presently available in the CREME96 model [14].

Of course, not all systems are required to operate at a 99%-reliability level. In many cases cost-effective design would be facilitated by the ability to assess system performance at various confidence levels, to see, for example, if a slightly lower reliability level in some components or sub-systems could reduce costs without significantly compromising overall performance. A comprehensive solar particle risk-assessment tool, which would enable designers to specify the solar particle environment at arbitrary severity levels, is therefore required.

In this paper, we present our first steps toward developing such a tool. In particular, we have made a new and complete analysis of the 23-year IMP-8/CRT timelines for high-energy He, CNO, and Fe fluxes, with full correction for instrumental dead-times. These corrections are especially important for the largest solar particle events. We have also analyzed the size distributions of fluxes and event-integrated fluences. We compare these distributions to the environment models presently available in CREME96 [14], both for solar-quiet times (during which Galactic cosmic rays dominate the near-Earth interplanetary environment) and for solar-active periods (in which ambient flux levels are enhanced by solar energetic ["flare"] particles). Finally, we use the observed distributions to make probabilistic predictions of mission-accumulated solar heavy ion fluences.

II. Chicago IMP-8/CRT Heavy-Ion Fluxes

We have used ion fluxes from the two primary detector channels of the IMP-8/CRT. The low-energy channel, corresponding to penetration through approximately ~30 mils Al-equivalent shielding, measures He at 11-20 MeV/nuc, CNO nuclei at 21-43 MeV/nuc, and Fe at 45-79 MeV/nuc. The higher energy channel measures He at 25-95 MeV/nuc, CNO at 45-211 MeV/nuc, and Fe at 97-432 MeV/nuc. The high-energy channel is generally more relevant to space-system design, since it corresponds to Al-equivalent shielding depths of ~100-1300 mils. He fluxes were collected in 33,430 six-hour bins between 30 October 1973 and 18 September 1996. Because of limited statistics, CNO and Fe fluences were accumulated in one-day and two-day bins, respectively.

A key feature of this analysis, especially for large solar particle events, is correction for instrumental "dead-time". This dead-time arises primarily from the active anti-coincidence shield which surrounds the sides of the CRT. During the peak rates of very large particle events, accidental coincidences between particles in this shield (primarily low-energy protons) and an ion in the telescope cause the telescope's count rate to be suppressed. The data must therefore be corrected for this underestimate of the true fluence. Moreover, the size of this correction depends upon the rate at which particles register in the anti-coincidence shield. A previous analysis of the IMP-8/CRT data [6] neglected this dead-time correction and therefore underestimated heavy-ion fluences. However, that analysis covered only 1973-83, during which the solar particle events had smaller low-energy proton rates than those of 1989-92 and hence required much more modest dead-time corrections than the very large events included in this study.

To determine this dead-time correction, we compared the IMP-8/CRT He rates to those reported by the GOES-7/MEPAD detector in two roughly comparable channels, which measure He rates at 15-45 MeV/nuc and 40-65 MeV/nuc. MEPAD He channels have not been as thoroughly characterized as the CRT or the MEPAD proton channels, and they may be background-dominated during low-rate periods. However, one very significant advantage of the MEPAD measurements is that they require no significant dead-time corrections, even in the very highest rate periods. Unlike CRT, MEPAD does not use an active anti-coincidence shield. MEPAD is also smaller (with a geometry factor of ~0.4 cm^2-sr, compared to CRT's ~2.0 cm^2-sr) and utilizes faster electronics, since it makes no attempt to identify heavier ions (which requires more extensive on-board processing of the detector signals[1]).

By determining the dead-time in many different time-bins in many different particle events, the correction factor was mapped out as a function of the particle rate in the CRT anti-coincidence shield. This correction function was then also applied to other ions (such as CNO and Fe) and to other solar particle events, including pre-1986 events for which no GOES data were available. When averaged over six-hour intervals, the deadtime corrections in solar particle events[2] were typically a factor of ~1.5, determined to within systematic uncertainty of ~10%. The largest dead-time correction, for the peak of the interplanetary shock event on 20 October 1989, was a factor of ~7, determined to within a factor-of-two residual systematic uncertainty.

It is perhaps worth noting that incomplete correction for dead-time may also have affected the Hopkins/Applied Physics Lab Charged Particle Measurement Experiment (CPME) instrument on IMP-8, which is the primary source for the solar proton data used in the JPL91 model. This instrument also has an active anti-coincidence shield. In general, daily fluences of >10 and >30 MeV solar protons from IMP-8/CPME and GOES-7/MEPAD agree to within ~10-20%. However, for the two-highest fluence days in Solar Cycle 22, the discrepancy is much larger. For 20 October 1989 and 24 March 1991, GOES-7/MEPAD reports >10 MeV proton fluences of 10.5 x 10^9 and 6.6 x 10^9 protons/cm^2-day, respectively. The corresponding values reported by the APL/CPME, however, are only 2.9 x 10^9 and 2.3 x 10^9 protons/cm^2-day. A similar disagreement is seen in the >30 MeV solar proton rates on these two days. This discrepancy may at least partially explain the departure from log-normal shown in JPL91's very highest daily proton rates [1].

Finally, it should be noted that the IMP-8/CRT timelines are only ~85% complete, primarily due to gaps in telemetry. By comparison with other satellites, we have confirmed that these datagaps did not cause the IMP-8/CRT to completely miss any significant solar particle event. Datagaps occurring during the declining phase of a

[1] An indirect confirmation of the relatively small dead-time in MEPAD comes from Chicago's Low Energy Telescope (LET), also on IMP-8. Like MEPAD, the LET lacks active shielding, is smaller than CRT, and uses faster electronics; and like MEPAD, the LET showed no evidence of saturation effects during the peak rates of the 20 October 1989 shock event.

[2] These dead-time corrections are the only significant correction for the CRT He fluences. However, for the CNO and Fe fluences, there is a similar correction related to the telescope's on-board priority logic and telemetry limitations on the pulse-height data, which is required to identify these ions. In general, this additional correction is a factor of ~3 in large solar particle events and can be reliably determined (to within ~10%) by internal consistency checks on the CRT telemetry stream.

solar particle event were filled in by interpolation or exponential fits to the available time bins. In a few cases, where an IMP-8/CRT datagap coincided with the rise or peak of a solar particle event, comparison to time profiles from other instruments (primarily the GOES-7/MEPAD He channels) were used to estimate the flux. To fill in datagaps during solar-quiet intervals (as identified by other instruments and satellites) we used IMP-8/CRT monthly-averaged cosmic-ray fluxes. These monthly-averages were also used to fill in the low-energy He, CNO, and Fe in an additional ~15-50% of the time bins, during which these channels reported zero counts because of low Galactic flux levels. As a result, downward statistical fluctuations in the low-energy channels are suppressed in the timelines presented below.

Figure 1 shows the fully-corrected timelines for the low and high-energy He, CNO, and Fe channels. The width of the trace in solar-quiet periods reflects statistical fluctuations as well as real short-term variability in the environment. Systematic errors during solar-quiet periods are believed to be small (~10%). Typical systematic error in solar particle events is ~20%, with larger error in the highest flux periods. The worst case is the 20 October 1989 shock event, in which the dead-time correction leaves a residual systematic factor-of-two uncertainty.

For comparison, the upper and lower solid horizontal lines in Figure 1 show the cosmic-ray-maximum and cosmic-ray minimum fluxes[3], respectively, for CREME96 solar-quiet models. The CREME96 cosmic-ray values match the observed extremes in the solar-quiet levels reasonably well.

The low-energy He channel in Figure 1 is very active, but solar particle events dominate the high energy He fluxes roughly 20% of the time during so-called "solar-active years" (1977.6-1984.6 for Cycle 21 and 1987.9-1994.9 for Cycle 22)[4], the seven years out of the ~ 11-year solar-activity cycle which encompass sunspot maximum and during which solar particle events are most likely to occur. (There are also a few events – roughly ~10% of the total – which occur during the remaining four, nominally "solar-quiet" years of the activity cycle.) Larger particle events were observed in Cycle 22 than in Cycle 21. However, Cycle 22's solar-active period appears to be effectively shorter than that of Cycle 21, in that 1993-95 is relatively quiet compared to 1983-85. Solar particle events are less noticeable at high energies and in the heavier ions. Nevertheless, even the high energy CNO and Fe channels show occasional factor of ~100 increases over cosmic-ray flux levels.

[3]Cosmic-ray maximum is generally referred to as "solar minimum" (and vice versa), since the Galactic cosmic-ray flux at Earth is anti-correlated with the solar activity cycle. Cosmic ray maximum/minimum, which may be less confusing than solar minimum/maximum in the present context, specifically connote solar-quiet flux levels which prevail in the absence of solar energetic particles.

[4]These dates for solar-active years roughly follow the useful but somewhat arbitrary definition given in JPL91. Specifically, the solar-active period begins two years before the sunspot maximum (determined to within the nearest 0.1 year) and persists for 7.0 years. However, we have shifted the start of the Cycle 21 solar-active period by ~3 months to include the very large particle event of September 1977.

III. Flux Distributions

Figure 2 shows probability distributions of the observed fluxes, in which the fluxes have been ranked in ascending order and plotted against the cumulative probability. The horizontal axis is mapped so that a log-normal distribution appears as a straight line [1]. In these plots, fluxes from solar-active years and from solar-quiet years are treated separately. Error bars have been suppressed, except for the very highest fluxes where systematic uncertainties are substantial. Figure 2 shows all the data points above 99% probability. At lower probabilities, the density of symbols has been suppressed in the plot by showing only a random sample of the the ~4000-30,000 points which were actually used in the probability analysis.

A. Flux Distributions in Solar-Quiet Years

Fluxes from solar-quiet years are shown as crosses in Figure 2. The solar-quiet probability distributions are relatively flat, at least up to high probability levels. No enhancements are seen in the high-energy CNO and Fe channels. The solid horizontal line in each panel shows the cosmic-ray maximum level from CREME96 [14]. Since the CREME96 cosmic-ray maximum is intended to represent a longer-term average than these ~daily fluxes, it is perhaps not surprising that this CREME96 flux intercepts the actual distribution near the middle. Because the solar-quiet-year distributions are so flat, the 90% flux exceeds the CREME96 cosmic-ray maximum level in each panel by no more than 50%, except in the case of the low-energy Fe channel[5], where the difference is a factor of ~3. However, these low-energy Fe nuclei are generally unimportant in space system design, since they are stopped by less than 100 mils shielding. At energies higher than those considered in Figure 2, the intrinsic variability in the Galactic cosmic ray flux is even smaller. Thus, for most applications, a formal "90% worst-case" environment (which is a frequent contractual obligation in system design but is not yet available in CREME96) is unlikely to give results which exceed those from the present CREME96 cosmic-ray maximum model by more than ~50%.

B. Flux Distributions in Solar-Active Years

Fluxes during solar active years are shown as circles in Figure 2. In each panel there is a clear population of enhanced flux levels, which diverges from the distribution at probability levels ranging from ~70% (for the low-energy He) to ~99% (for the high-energy CNO and Fe channels). These enhanced fluxes roughly follow log-normal distributions, at least up to ~99.9%, where in some cases there appears to be a flattening. However, this flattening is not clearly established because of the large systematic uncertainties in these very high flux measurements. In all panels, the highest fluxes come from the 20 October 1989 shock event.

[5]This low-energy Fe distribution may be distorted by the large number of time bins (~50%) in which the flux was too low to be measured.

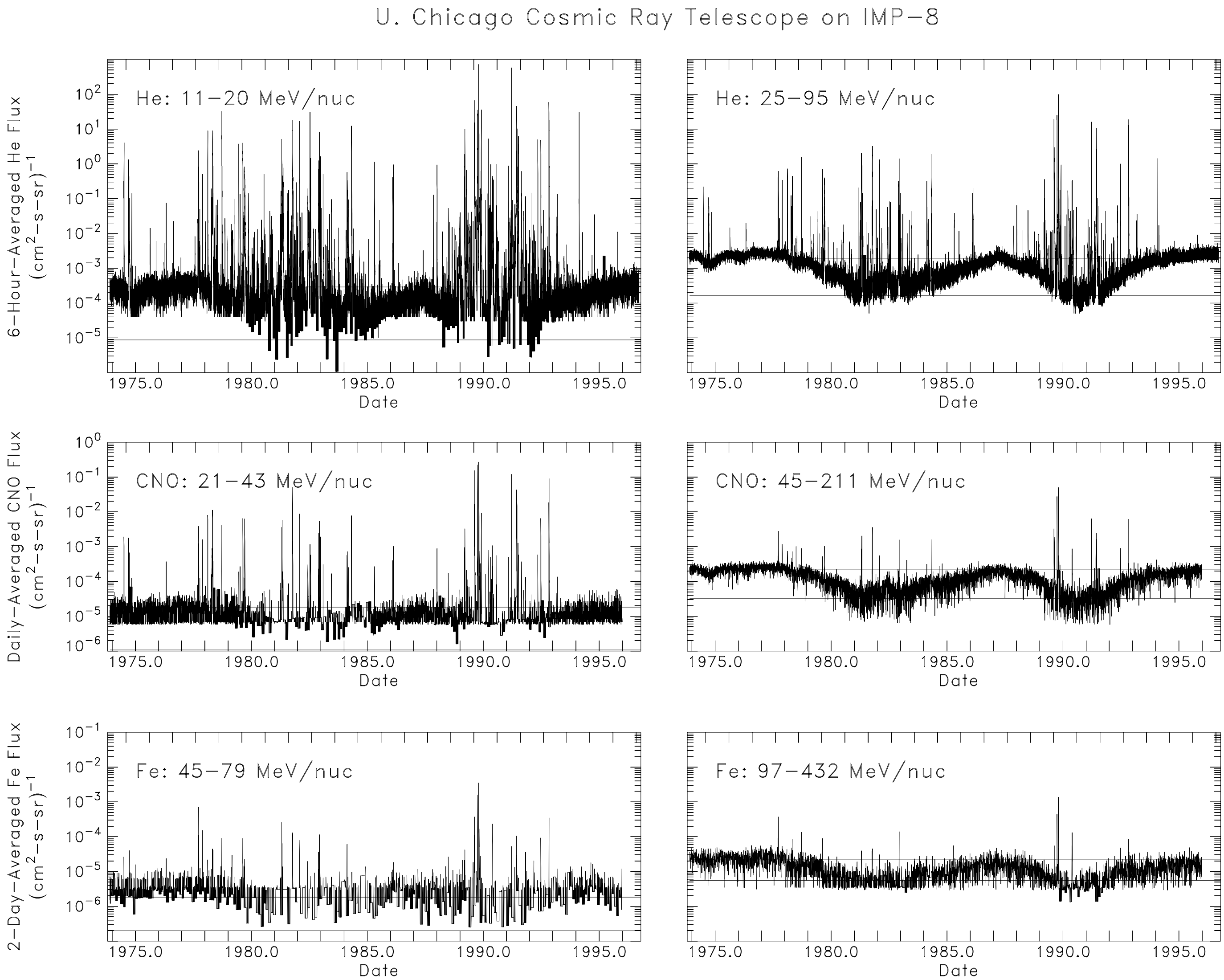

Fig. 1. Heavy-ion flux timelines from the University of Chicago's Cosmic Ray Telescope (CRT) on IMP-8 for 1973.8-1996.

Flux levels in most solar particle events are relatively stable for at least several hours after reaching maximum. Thus, the six-hour averaging used for the He provides a reasonably good estimate of the peak flux. Peak fluxes exceed the daily- and two-day averages used for the CNO and Fe, but not by more than an order of magnitude. Thus, the fluxes in Figures 1 and 2 may serve as rough proxies for the peak fluxes, which are often the primary concern for system operation during solar particle events.

The dashed horizontal line in each panel of Figure 2 shows the "worst-day" solar particle flux from CREME96 [14]. This model, which was derived by averaging over 18 hours of the 20 October 1989 shock event, was designed to provide a credible worst-case environment for evaluating peak-rate effects in space-system design. As one might expect, the highest six-hour He fluxes in Figure 2 fall slightly above this "worst-day" average, while the highest observed daily-CNO and two-day-Fe fluxes match the model's levels reasonably well. Comparison with the observed probability distributions in Figure 2 confirms that the CREME96 "worst-day" model does indeed represent a 99.9%-worst-case peak-rate environment[6].

Particularly noteworthy in Figure 2 is the steepness of the solar-active-year probability distributions. In fact,

[6] CREME96 also has two other solar particle models: a "worst-week" model, which is discussed in Section IV below, and a "peak flux" model, which is described in more detail in [14]. The "peak flux" model was derived using the peak 5-minute-averaged GOES proton fluxes on 20 October 1989. The CREME96 "peak flux" model gives fluxes which exceed those of the "worst-day" model by typical factors of ~3-5, varying with energy and species. Because of difference in time-scale, the "peak-flux" model is not directly comparable with the distributions shown in Figure 2, thus making it difficult to quote a specific corresponding confidence level.

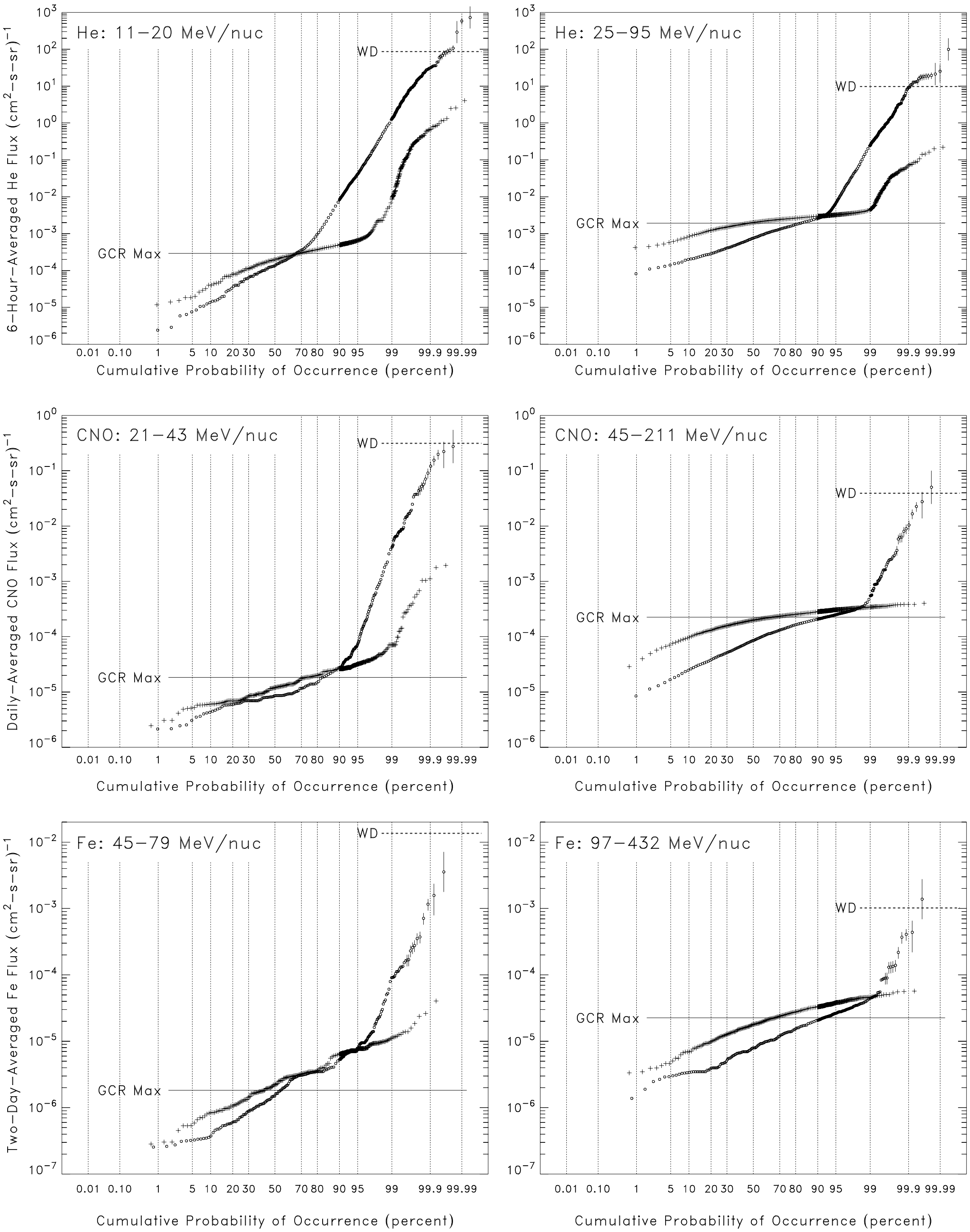

Fig. 2. Cumulative probability distributions of fluxes during solar-active years (circles) and solar-quiet years (crosses). Horizontal lines mark flux levels from CREME96 cosmic-ray maximum model (solid line, "GCR Max") and "worst day" solar particle model (dashed line, "WD").

these heavy ion fluxes grow with increasing cumulative probability much more rapidly than the daily-proton rates in the JPL91 solar proton model [1]. Designing to an even slightly lower reliability level can therefore correspond to a highly significant reduction in the heavy-ion radiation hazard, substantially below the CREME96 levels. However, comparing the various panels of Figure 2 shows that the size of the reduction depends upon energy and species, and hence upon shielding, orbit, and device characteristics.

IV. Event-Size Distributions

For many applications accumulated fluence is a more relevant consideration than peak flux. In order to calculate accumulated fluences, the fluxes shown in Figure 1 must be time-integrated into "events". The typical duration of one of these events is about 10 days, and an event often comprises several successive flux increases. (For this reason, perhaps these "events" should be referred to as "episodes".) For example, the 19-27 October 1989 episode, which we treat in this analysis as a single "event", was actually caused by three distinct coronal mass ejections (CMEs), erupting on 19, 22, and 24 October and all associated with the same active region as it travelled across the face of the Sun. Each of these very fast CMEs drove an interplanetary shock which caused energetic particle fluxes at Earth to increase by more than three orders of magnitude above normal levels. Moreover, the 19 October CME erupted from near the center of the solar disk. The most intense region of the interplanetary shock driven by this CME actually hit Earth, increasing ambient flux levels by yet another order of magnitude for a period of ~3-6 hours. These four extreme and rare occurrences were obviously related, in that they arose within a short timeframe from the same active region. A modeling technique which ignored this obvious correlation and treated each flux increase as an independent "event" would systematically underpredict the probability of such a sequence of events and the very large fluence thereby accumulated.

Event start- and end-times therefore should be chosen so that related increases are combined into a single event but that unrelated occurrences are treated separately. Defining solar particle events in the flux timelines is thus to some extent a matter of judgement. For this study, we began with the events given in previously published catalogues [1], [15]. We supplemented these lists with a few smaller events from 1986-1991 not explicitly mentioned in those references, as well as a few events from the years 1992-95, which were not covered by the earlier surveys. We identified these additional events from IMP-8/CPME database as available through OMNIWeb [16].

We selected for further analysis only those events in which the accumulated fluence of >10 MeV protons exceeded 10^7 protons/cm^2. This criterion is the same as used in JPL91 for this proton channel. This threshold is also probably a reasonable starting point for events relevant to space-system design, since it corresponds to roughly an order-of-magnitude increase over the typical Galactic proton fluence during one of these events[7].

With this selection criterion, we identified 95 solar particle events, covering 1038 days in total, between Day 303 of 1973 and Day 289 of 1996. All but eight of these events fell during the 14.1 solar-active years covered by this study, corresponding to an average of 6.17 events per solar-active year. This average is somewhat smaller than the 6.75 events per solar-active year given by JPL91 based on Day 331 of 1963 to Day 126 of 1991. This discrepancy is due almost entirely to the relative dearth of significant solar particle events in 1993.0-1994.9.

By using total proton fluence to identify events, we correctly quantify the probability of high-energy heavy ion enhancements, without introducing the significant selection-biases which would have arisen if we had identified events by heavy-ion fluences *per se*. However, Galactic cosmic rays (GCRs) make a significant and often dominant contribution to the high-energy heavy-ion channels in many of the events. This background is illustrated in the top panel of Figure 3, which shows the distribution of observed event-integrated fluences for the high energy CNO channel. The dashed line in this panel shows the approximate GCR background, as estimated by a 10-day accumulation of cosmic-ray-minimum GCR flux. This dashed line is, of course, only a rough estimate in that it does not take into account event-to-event variation in duration and the contemporaneous GCR flux.

The bottom panel of Figure 3 shows the event-size distribution again, after the contemporaneous GCR background (as determined from the IMP-8/CRT monthly averages) has been subtracted from each event[8] and the rankings re-calculated. Events in which the observed fluence was less than or equal to the GCR background have fallen off the plot, but are still counted when determining the other events' rankings. The distribution is now reasonably well-described by a log-normal. Also, the log-normal fit after GCR-background subtraction is significantly different from the one in the top panel, which was fit to just the highest-fluence events alone.

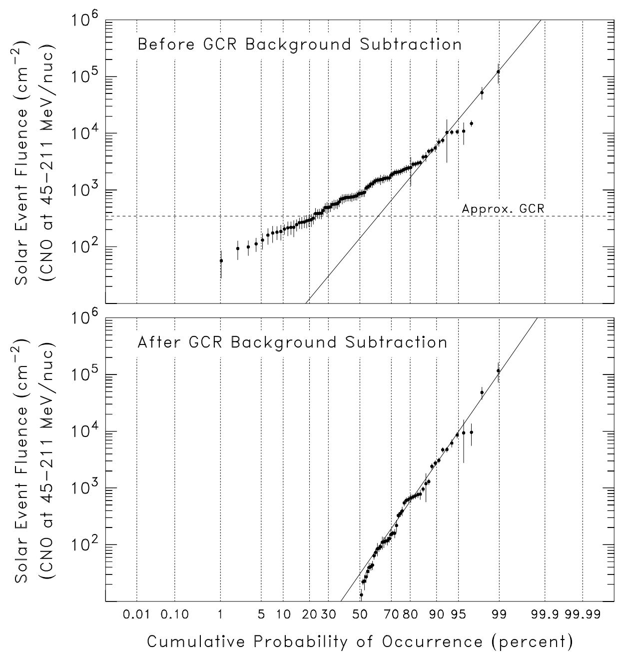

Fig. 3. Cumulative probability distribution for the time-integrated fluences of high-energy CNO ions in solar particle events before (top panel) and after (bottom panel) subtracting Galactic cosmic-ray background. See text for details.

[7] This comparison is, of course, somewhat disingenuous, since Galactic and solar protons have vastly different energy spectra!

[8] Subtracting the GCR background is also important for applying these results to low-Earth orbits, since solar heavy ions have lower ionic charge states [7], [8] than Galactic cosmic rays and hence enhanced geomagnetic access. This difference is especially important for Fe [14].

Figure 4 also shows GCR-subtracted fluence distributions for the other ions and energy-bins. These distributions are based on all 95 events, including the eight which occurred during solar-quiet years. The distributions are reasonably consistent with log-normal distributions, except for the flattening at small He fluences. This flattening is presumably a reflection of the bias against small events introduced by our minimum-proton-fluence criterion. In each panel the highest fluence belongs to the 19-27 October 1989 event, and fluences extend downward to events which are smaller by three orders of magnitude or more. The solid lines show log-normal distributions determined by least-squares fits to the datapoints with probability above 70%. The parameters for these fits are given in the panels. Except for the high-energy Fe, the slopes of these distributions (as reflected by $\sigma \approx$ 1.2-1.5) are larger than those of the >10, >30, and >60 MeV event-integrated proton fluences in the JPL91 model ($\sigma \approx$ 1.0-1.1). Thus, reductions in the cumulative probability level correspond to relatively larger fluence reductions for heavy-ions than for protons.

The horizontal dashed lines in Figure 4 show fluences from the CREME96 "worst-week" model, which was derived from data accumulated over the entire 180 hours of the 19-27 October 1989 event[9]. This "worst-week" model is designed for evaluating effects related to total accumulated fluence in a single event. Comparisons with the log-normal fits in Figure 4 confirm that the CREME96 "worst-week" model does indeed represent a ~99%-confidence-level worst-case event, although the formal confidence level is not exactly the same in each panel.

V. Mission-Accumulated Fluences

Probabilistic predictions of mission-accumulated fluences can be calculated using the log-normal fits in Figure 4 and Monte Carlo techniques equivalent to those used in JPL91. Specifically, consider a mission lasting T solar-active years. We first randomly sampled the number of events in the mission from a Poisson distribution with mean μT, where μ is the average number of events per solar active year ($\mu =$ 6.17 in this analysis). Each event's fluence was then sampled from the appropriate log-normal distribution, and the fluence from all the events was summed up. We repeated this calculation for a large number of "missions" and ranked the accumulated fluences to produce cumulative probability curves in Figure 5. To get curves which were smooth even at the lowest probabilities generally required 10^5 - 10^6 repetitions[10]. Note that this technique for calculating mission-accumulated fluences implicitly assumes: (1) that the events are independent and uncorrelated and (2) that all solar-active years are alike, apart from statistical fluctuations in the number and sizes of events. Both of these assumptions are open to question, but the limited dataset on well-measured particle events makes more complicated formulations problematical.

The various curves in each panel of Figure 5 are results for missions lasting 1, 2, 3, 5, and 7 solar-active years. Although these results are tied to the IMP-8/CRT energy intervals, they may be useful since they are, to our knowledge, the first such calculations for solar heavy ions. Figure 5 represents the fluences of *solar* heavy ions *only*. For the He channels and the low energy CNO and Fe channels, the contributions from Galactic cosmic rays and other sources are negligible by comparison. However, in the high-energy CNO and Fe channels the Galactic cosmic rays should also be taken into account. The vertical dashed lines in those two panels show the annual GCR accumulation at cosmic-ray minimum and cosmic-ray maximum flux levels. Depending upon the required confidence level, mission duration, and when the mission is flown, the additional solar contribution may or may not be important. Roughly speaking, the cosmic-ray-*maximum* GCR fluence is equivalent to the ~90$^+$% confidence-level upper limit on the one-year solar fluence in the high energy CNO and Fe channels. In terms of mission-accumulated fluence at these high energies, building to a cosmic-ray-maximum environment should be sufficient unless an extraordinarily high confidence level is required or the mission is to a low-Earth orbit to which solar Fe ions have preferential geomagnetic access [14].

VI. Discussion

The Chicago IMP-8/CRT is an unrivaled source of data on the heavy-ion environment relevant to spacecraft design. This analysis demonstrates that these data are of sufficient quality and quantity to tackle the heavy-ion component of a comprehensive solar-particle risk-assessment tool, which would allow designers to investigate the solar-heavy-ion hazard at arbitrary confidence levels. Moreover, these results indicate that such a capability would significantly reduce design margins and hence costs, since even a modest decrease in the required reliability level corresponds to a substantial reduction in the intensity of the solar-heavy-ion environment. Pending the development of such a tool, the results presented here should be useful in deciding when a more careful analysis of the solar-heavy-ion hazard is necessary.

However, the results presented here are not sufficient in themselves to undertake quantitative analyses, and further work is required. In particular, spectral shapes at high-

[9] The datapoints for the October 1989 event shown in Figure 4 do not exactly match the fluence levels from the CREME96 "worst-week" model. The "worst-week" model was derived by an independent analysis, which included data from other instruments (besides the IMP-8/CRT) and fits to spectra subdivided into as many energy bins as the ion statistic would allow [4]. These differences account for the slight discrepancies in the CNO and Fe fluence levels. The discrepancies in the He channels are larger (a factor of ~4) because the "worst-week" model presently contains a preliminary estimate of the October 1989 He fluence [4] which was made before the IMP-8/CRT He fluences shown here were available. The discrepancy is larger than we anticipated, and further analysis of the October 1989 He fluences is in progress. However, the revision in the worst-week He fluences suggested here will not have a significant impact on most design studies.

[10] We confirmed that our software reproduced the mission-accumulated proton fluence curves given in Figures 4a-4e of JPL91 when we used their parameters, apart from the error in their horizontal axis label. (The fluence units in Figures 4a-4e of JPL91 are actually cm^{-2}, not cm^{-2}-sr^{-1}.)

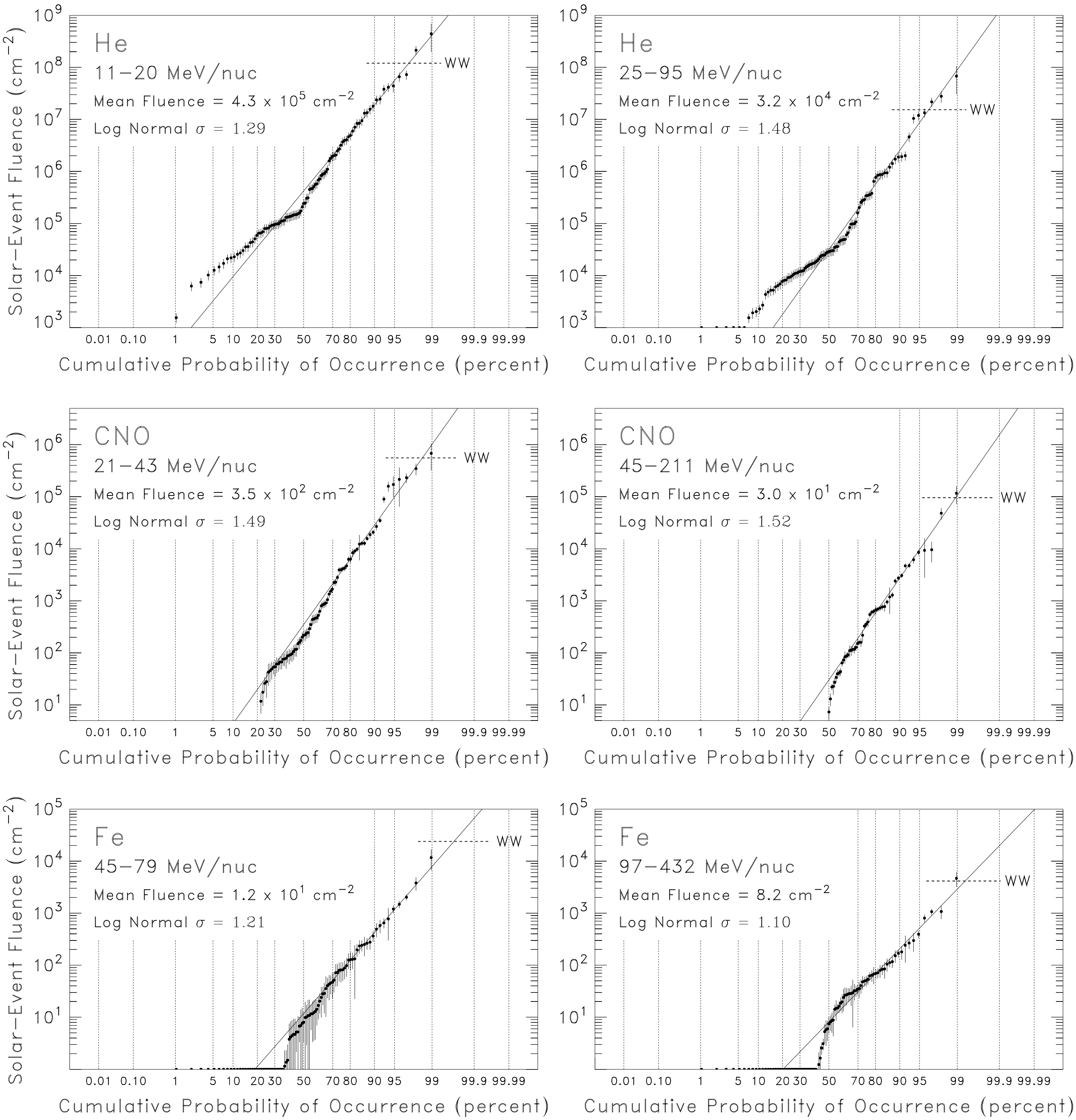

Fig. 4. Cumulative probability distributions of solar particle event fluences for all the heavy-ion channels studied here, after GCR background subtraction. (The middle panel on the right is the same as Figure 3b.) Solid lines show the log-normal fits, whose parameters are given in the insets. Horizontal dashed lines ("WW") show fluence levels from the CREME96 "worst week" solar particle model.

energy exhibit tremendous variability [11]. The broad high-energy bins used in this initial study make it difficult to assess how effectively the high-energy flux can be attenuated by shielding. Microelectronic devices show single-event effects over a wide range of threshold linear-energy-transfers (LETs). The high-energy relative abundances of the other major species should therefore also be characterized as thoroughly as possible. In order to evaluate solar-

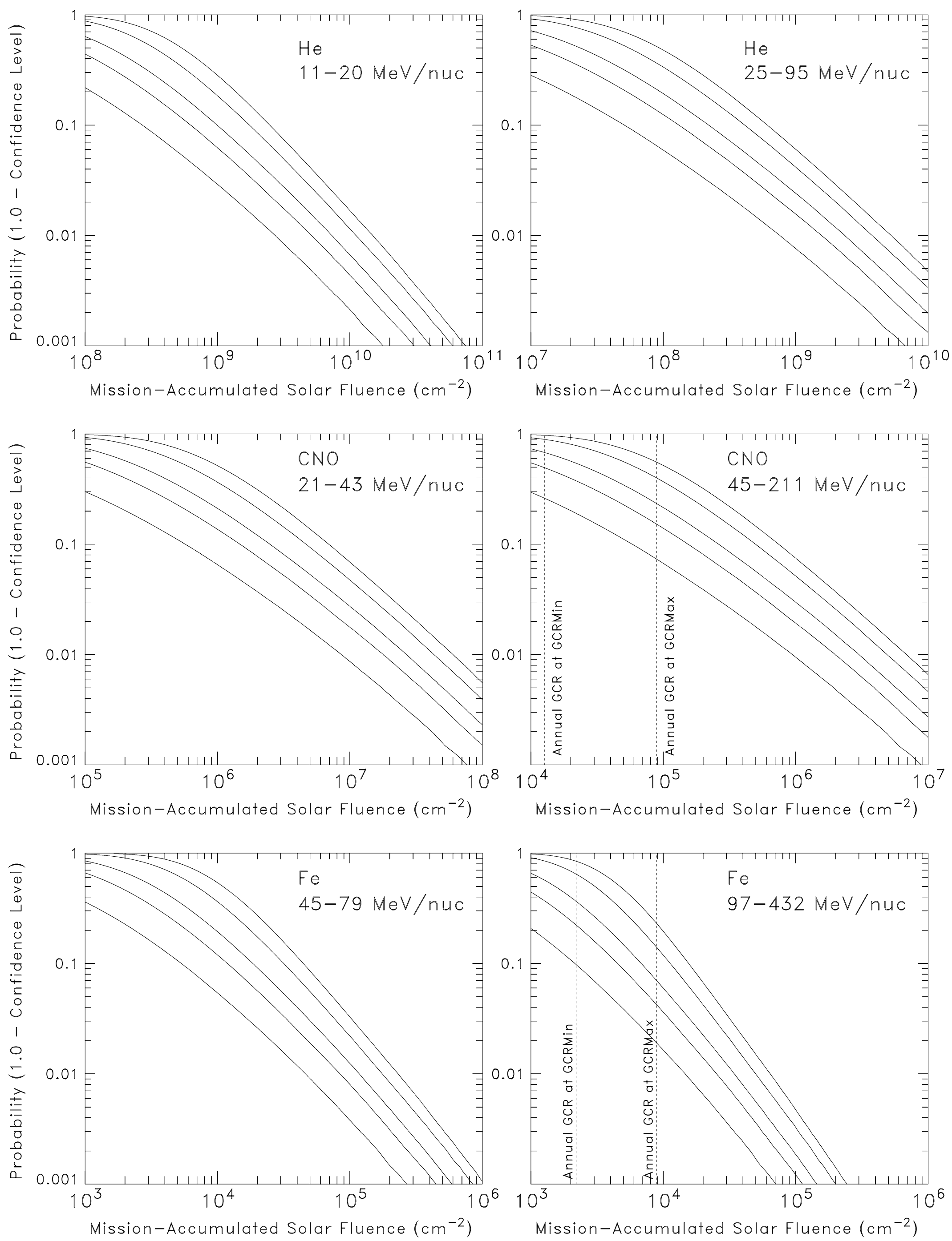

Fig. 5. Predictions of mission-accumulated solar-heavy ion fluences. The curves are for mission durations of 1, 2, 3, 5, and 7 solar-active years.

cell damage, it will also be necessary to supplement the He data shown here with lower-energy measurements. Since devices are often vulnerable to both proton- and heavy-ion-induced effects, these results should be coupled with a solar proton model which extends to at least 100 MeV. Finally, in order to make accurate calculations in low-Earth orbits, these solar particle events must also be correlated with geomagnetic disturbances.

Of course, the applicability of conclusions drawn from this work will always be constrained by the extent to which the past two Solar Cycles reasonably represent the intrinsic variability in the Sun's high-energy particle output. From the IMP-8/CRT historical record, it is clear that October 1989 does indeed constitute at least a 99%-confidence-level worst case event. How it would rank in a longer historical survey is largely imponderable. From the standpoint of space-system design, there is insufficient high-energy data on the August 1972 event to decide if that event really would have constituted a more severe environment than October 1989[11]. The historical record does suggest that there may indeed have been even larger particle events and Solar Cycles in the past[17]. On the other hand, perhaps such worries should be tempered by thoughts of how simple satellite design would have been during the Maunder Minimum.

VII. Acknowledgments

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